

The Role of WiMAX Technology on Broadband Access Networks: Economic Model

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1. Introduction

The increasing demand of quadruple-play services, including video, voice, data and mobility, has created new challenges to the modern broadband wireless/wired access networks (Pereira & Ferreira, 2009). Moreover, with the proliferation of broadband applications, the need for comprehensive broadband infrastructure becomes critical (Fong & Nour, 2004).

Broadband in the OECD is still dominated by DSL (Digital Subscriber Line) but there is an obvious trend emerging to upgrade last-mile access networks to support the new services requirements (OECD, 2008). To address these network requirements, many carriers in emerging markets will have to move from legacy platforms toward next-generation solutions with a combination of wireless and wireline technologies, such as worldwide interoperability for microwave access (WiMAX), IP-Ethernet, new forms of DSL technology and fiber.

In this context, several broadband access technologies are being deployed to address the bandwidth bottleneck for the "last mile," the connection of homes and small businesses to this infrastructure. There are many competing technologies which can provide the bandwidth required to deliver broadband services, but each technology has its limits in terms of bandwidth, reliability, cost or coverage (Corning, 2005). Some of the most important last-mile solutions include xDSL, HFC, FTTH, PLC, Satellite, and the fixed broadband wireless access network.

In general, broadband access technologies can be classified by the physical medium in two major groups, namely wired and wireless technologies (Corning, 2005; Fernando, 2008; Ims *et al.*, 2004).

1.1 Broadband Wired access technologies

Dominant broadband wired access technologies today are DSL and Hybrid Fiber Coaxial (HFC) networks. Nevertheless, copper based access networks still represent the overwhelming share of fixed telecommunications access network infrastructures around the world (Fernando, 2008; Sigurdsson, 2007).

DSL networks have been gradually developing over the past several decades but all share the same principle of connecting households within a given area to a central office with an

individual pair of Unshielded Twisted Pair (UTP), called the local loop (Figure 1). DSL technology uses existing twisted-pair phone lines for broadband connection. The main limitation of this technology is that the transmission speeds decreases when copper local loop length increases.

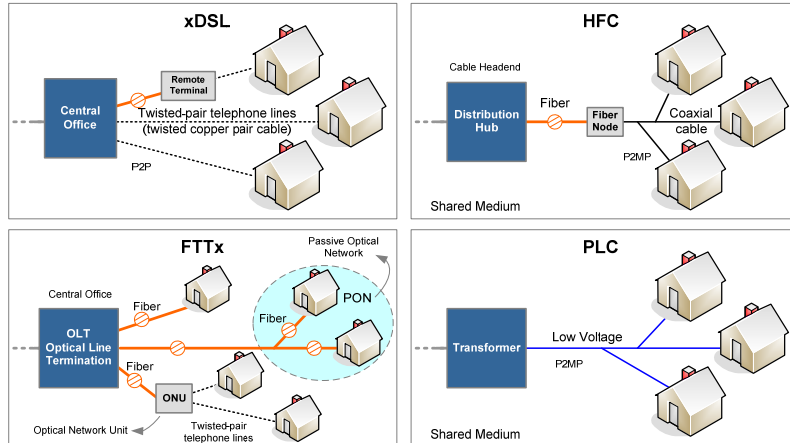


Fig. 1. Wired access networks

An HFC network is normally a cable television network that includes a combination of optical fiber (between head end and the fiber node) and coaxial cables (from fiber nodes to CPE). Initially, the original HFC networks were designed to support only downstream broadcasts. Currently, upstream traffic must also be supported using Cable Modems (CM) for full Internet access. The bandwidth provided by cable networks will allow for 160 Mbps downstream and 120 Mbps upstream for end-users (using Docsis 3.0 standard). HFC uses a shared medium, therefore the bandwidth will also have to be shared by end-users. Typically there are 500-1000 subscribers in a single local distribution point, which can be brought down to about 250 on average.

The FTTH (PON) technology connects Optical Line Terminal (OLT) at the Central Office (CO) to Optical Network Units (ONUs) at subscribers homes and businesses over one wavelength in the downstream and another wavelength in the upstream (from ONUs to OLT). This technology provides much higher bandwidth than DSL and Cable Modem. A PON can cover a maximum distance of 20 km from the OLT to the ONU. Under normal conditions, PON allows 16 ONUs at a maximum distance of 20 km from the OLT and 32 ONUs at a maximum distance of 10 km from the OLT supporting up to 1 Gbps.

Power Line Communications is a broadband access technology that uses the low and medium voltage electricity grid to provide telecommunication services (Little, 2004). The Low Voltage (LV) electrical power distribution network represents the most attractive medium for high-speed digital communication purposes due to an ever-increasing demand caused by the advances in communication and information technologies (Lim *et al.*, 2000). Notwithstanding the benefits that the availability of an extensive infrastructure can allow, for the moment the service provision is far from standardized, and the capacity of bandwidth provided through BPL is still being questioned (Sarrocchio & Ypsilanti, 2008).

1.2 Broadband Wireless Access Networks

Generally, wireless broadband refers to technologies that use point-to-point or point-to-multipoint microwave in various frequencies between 2.5 and 43 GHz to transmit signals between hub sites and an end-user receiver. At network level, they are suitable for both access and backbone infrastructure so, it is in the access network where wireless broadband technology is actually proliferating. As a consequence, the terms “wireless broadband” and “wireless broadband access” are used interchangeably (Corning, 2005). However, current wireless access networks show limits in terms of data rate and QoS (El Zein & Khaleghi, 2007).

Wireless broadband is the “great equalizer” of broadband technologies. It enables even those without twisted copper, coaxial cable, fiber, or satellite to enter competition for the broadband dollar. It therefore expands the definition of who can be a carrier (WiMAX Forum, 2005b). Unlike fixed technologies, wireless solutions are flexible and scalable, both in terms of their physical layout and their logical architecture. Due to the cost advantages associated with wireless and the use of unlicensed spectrum bands, infrastructure investments are now within the reach of local organizations which are able to better understand local conditions. Covering sparsely populated areas is not economically viable for the use of conventional techniques. The newest wireless technologies encourage a different model of infrastructure development, better suited to the challenges of extending Internet connectivity to rural areas, and thus becoming a solution that offers wide-area coverage well suited to small villages (Sarrocchio & Ypsilanti, 2008) (Fernando, 2008). The infrastructure can therefore expand from the bottom-up, without a preconceived plan, linked to the needs and attributes (geographical, demographic, and economic) of local communities. The distribution of telecommunications infrastructures has traditionally been associated with hefty investment programs undertaken by large entities such as telecommunications operators and government agencies (Galperin, 2005).

Wireless networking technologies can be divided into three main categories (Carcelle *et al.*, 2006). Each addresses specific requirements and purposes in point-to-point and point-to-multipoint communication (see Fig. 2).

The range performances for a WPAN is typically from 1 meter to a few dozens meters, and is designed for low data rate (usually 100-200 kbps). WPAN technologies comprise: ZigBee, Bluetooth and UWB. In WLAN technologies the range performances are typically from a few dozen meters indoors to a few hundred meters outdoors, and are designed for high data rate (usually 1 to 20 Mbps). One technology of this family is Wi-Fi. The WWAN is mainly focused for long-distance point-to-point connections with high data rate.

Wireless broadband access systems have been deployed at frequencies ranging from 400 MHz to about 30 GHz (Lehr *et al.*, 2004). Different parts of the spectrum have dramatically different physical properties. For example, at 30 GHz, signals attenuate rapidly with distance, they are limited by rainfall, and to Line-of-Sight (LOS) deployments. These frequencies have been used most often as a substitute for high-capacity point-to-point links such as those used by service providers and large enterprise customers to connect backbone nodes or buildings. In contrast, at lower frequencies, below say 10GHz, the spectrum is much more encumbered by legacy incumbents and licensees are typically limited to smaller bandwidth channels. However, the spectrum is less susceptible to interference from rainfall and can operate in Non-Line-of-Sight (NLOS) situations (e.g. it reaches inside buildings to a desktop or mobile antenna), and requires less costly technology. The lower the frequency,

the better the penetration of buildings or of foliage, besides immunity to rainfall, but there is less bandwidth available.

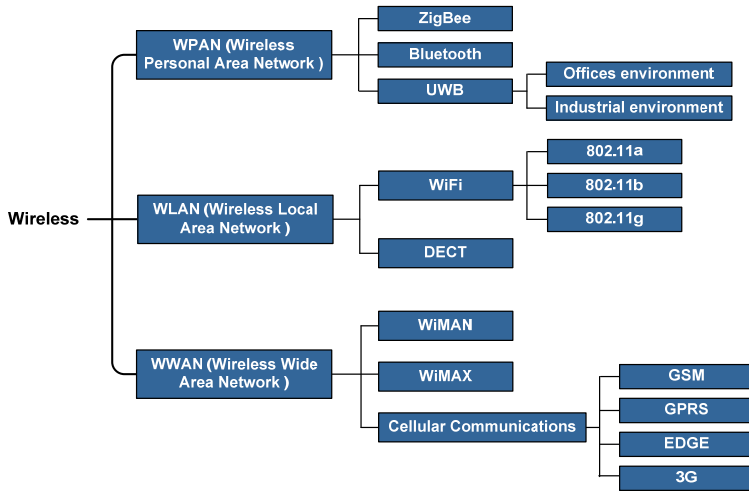


Fig. 2. Wireless technologies taxonomy (Carcelle *et al.*, 2006)

If we look from the line of sight perspective, wireless technologies can be broadly categorized into those requiring Line-of-Sight (LOS) and those that do not (NLOS) (Corning, 2005): Line of sight means that there is an unobstructed path from the CPE antenna to the access point antenna. If the signal can only go from the CPE to the access point by being reflected by objects, such as trees, the situation is called non-line of sight. NLOS systems are based on OFDM, which combats multipath interference, thereby permitting the distance between the CPE and the access point to reach up to 50 kilometers in the MMDS band. However, NLOS systems are more expensive than LOS systems (Ibe, 2002).

2. WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is a standardized form of wireless metropolitan area network (WMAN) technology that has historically been based on proprietary solutions, such as MMDS and LMDS. The first version of the IEEE 802.16 standard was completed in October 2001 and defines the air interface and medium access control (MAC) protocol for a wireless metropolitan area network, intended to provide high-bandwidth wireless voice and data for residential and enterprise use (Ghosh *et al.*, 2005). This standard was followed by the 802.16a standard in early 2003. Both standards support peak data rates up to 75 Mbps and have a maximum range of about 50 km. Because WiMAX systems have the capability to address broad geographic areas without the costly infrastructure requirement to display cable links to individual sites, the technology may prove less expensive to expand and should lead to more ubiquitous broadband access (Peng & Wang, 2007).

Wireless broadband promises to bring high-speed data to multitudes of people in various geographical locations where wired transmission is too costly, inconvenient, or unavailable

(Salvekar *et al.*, 2004). The 802.16 standard uses Orthogonal Frequency Division Multiple Access (OFDMA), which is similar to OFDM in the way that it divides the carriers into multiple sub-carriers. OFDMA, however, goes a step further by then grouping multiple sub-carriers into sub-channels. A single client or subscriber station might thus transmit using all of the sub-channels within the carrier space, or multiple clients might also transmit with each using a portion of the total number of sub-channels simultaneously (Konhauser, 2006). In the RF front-end, WiMAX uses OFDM, which is robust in adverse channel conditions and enables NLOS operation. This feature simplifies installation issues and improves coverage, while maintaining a high level of spectral efficiency. Modulation and coding can be adapted per burst, ever striving to achieve a balance between robustness and efficiency in accordance with prevailing link conditions.

Service providers will operate WiMAX both on licensed and unlicensed frequencies. The technology enables long distance wireless connections with speeds up to 75 Mbps. This can provide very high data rates and extended coverage. However:

- 75 Mbps capacity for the base station is achievable with a 20 MHz channel at best propagation conditions. But regulators will often allow only smaller channels (10 MHz or less) reducing the maximum bandwidth.
- Even though 50 km is achievable under optimal conditions and with a reduced data rate (a few Mbps), the typical coverage will be around 5 km with indoor CPE (NLOS) and around 15 km with a CPE connected to an external antenna (LOS).
- To keep from serving too many customers and thereby greatly reducing each user's bandwidth, providers will want to serve no more than 500 subscribers per 802.16 base station (Vaughan-Nichols, 2004).

One of the main advantages of this technology is the capacity to deploy broadband services in large areas without physical cables. These characteristics give to telecommunication supplier the capacity to implement new broadband telecommunication infrastructures very quickly, and with a lower cost than the wired networks.

To sum up, the main advantages of the WiMAX technology in relation to other connection technologies are: it does not need cable installation, which can solve the access problem to remote places; it is rather quick to deploy. This technology could have an access velocity which is 30 times higher than basic ADSL technology. Besides frequency range is between 2 and 11 GHz, with the maximum range of 50 km from the base station, and data transmission to 70 Mbps. So, one BS sector can serve different businesses or many homes with DSL-rate connectivity. Another advantage is the high capacity to service modulation (data and voice), to perform symmetric transmission (the same velocity to send and receive data) and the use of QoS.

2.1 System Architecture

A fixed broadband wireless access network is essentially a sectorized network, composed of two key elements: base station (BS) and customer premises equipment (CPE). The BS connects to the network backbone and uses an outdoor antenna to send and receive high-speed data and voice to subscriber equipment, thereby eliminating the need for extensive and expensive wireline infrastructure and providing highly flexible and cost-effective last-mile solutions.

FWA base station equipment multiplexes the traffic from multiple sectors and provides an interface to the backbone network. For each sector, a radio transceiver module and a sector antenna is also required. The multiplexer (such as a switch) aggregates the traffic from the

different sectors and forwards it to a router that is connected to the service provider's backbone IP network (Ibe, 2002). The backbone connection can be provided with a point-to-point radio link or a fiber cable, and can be either IP or ATM-based. The distance between the CPE and the BS depends on how the system is designed and the frequency band in which it operates. The CPE with an indoor antenna can be installed by the customers themselves, whereas the outdoor antenna requires a technician to install it (Smura, 2004). When we need to define a point-to-multipoint wireless system, several parameters are very important: the characteristics of the geographical area (for example, mountains), the subscriber density, the bandwidth required, QoS, the number of cells, etc. In areas with a low traffic demand and/or low subscriber density, the most important factor is the radio coverage whereas in areas with a high traffic demand and/or high subscriber density, capacity becomes a more important issue. Through a careful selection of network design parameters, tradeoffs can be made between coverage and capacity objectives to best serve the end users within the service area (Wanichkorn, 2002).

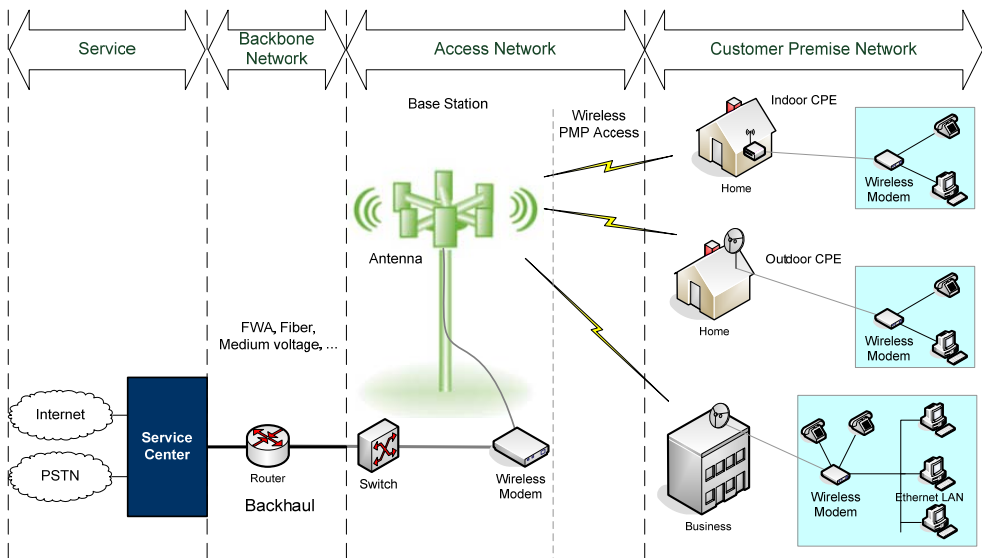


Fig. 3. WiMAX System Architecture

The WiMAX wireless link operates with a central BS through a sectorized antenna that is capable of handling multiple independent sectors simultaneously.

2.2 System Components

As previously referred to, base station equipment and customer premise equipment are the two main components of WiMAX architecture for the access network. The CPE enables a user in the customer's network to access Wide Area Network (WAN). The BS controls the CPEs within a coverage area, and consists of many access points or wireless hubs, each of which control the CPE in one sector. The following figure shows the basic components of a radio communication system.

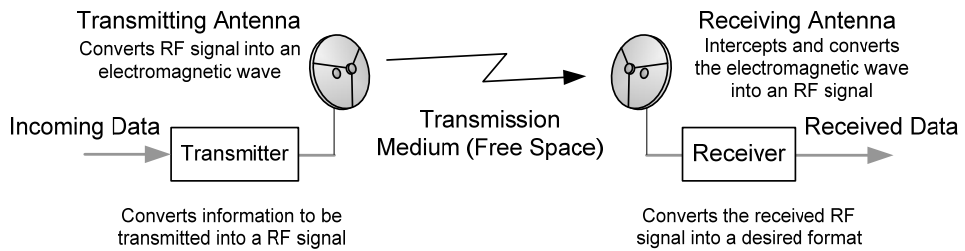


Fig. 4. Components of a radio communication system (Ibe, 2002)

2.2.1 Customer Premise Equipment – CPE

Residential CPEs are expected to be available in a fully integrated indoor self-installable unit as well as indoor/outdoor configuration with a high-gain antenna for use on customer sites with lower signal strength (Ohrtman, 2005). In most cases, a simple plug and play terminal, similar to a DSL modem, provides connectivity. For customers located several kilometers away from the WiMAX base station, an outdoor antenna may be required to improve transmission quality. To serve isolated customers, a directive antenna pointing to the WiMAX base station may be required.

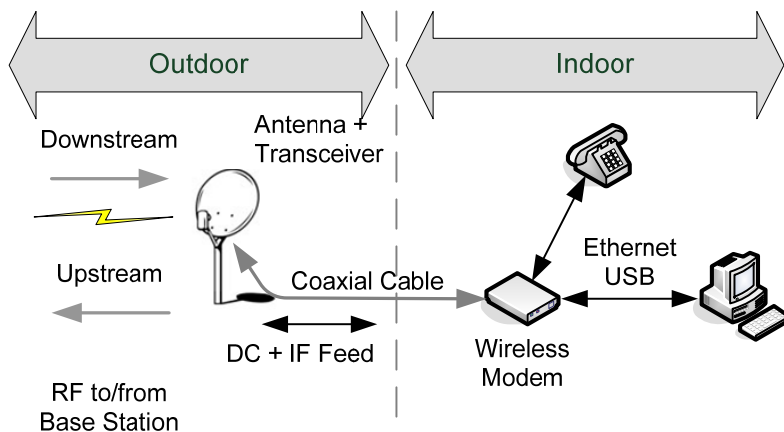


Fig. 5. FWA Subscriber Configuration (Outdoor CPE)

CPE or terminals are expected to be available in a number of configurations for customer specific applications and for different types of customers. Households in multi-tenant buildings can be served by installing a high throughput WiMAX outdoor unit with a low to medium capacity DSLAM (Digital Subscriber Line Access Multiplexer) as an in-building access device utilizing the in-building telephone wiring to reach individual apartments or by installing an individual WiMAX terminal in each household (WiMAX Forum, 2005a). These units are priced higher for the business case, consistent with the added performance (WiMAX Forum, 2004).

FWA CPE is often divided into three main components parts (Fig. 5): the modem, the radio, and the antenna. The modem device provides an interface between the customer's network and the fixed broadband wireless access network, while the radio provides an interface

between the modem and the antenna. As a matter of fact, some vendors integrate these two components to form a compact CPE, while others have the three units as standalone systems (Ibe, 2002). The CPE antenna type depends on the Non-Line-of-Sight capabilities of the system. In a Line-of-Sight FWA network, the CPE antennas are highly directional and installed outdoors by a professional technician. In Non-Line-of-Sight systems, the beamwidth of the CPE antenna is typically larger, and in the case of user-installable CPE's the antenna should be omnidirectional (Smura, 2004).

2.2.2 Base Station Equipment

The capacity of a single FWA base station sector depends on the channel bandwidth and the spectral efficiency of the utilized modulation and coding scheme. WiMAX systems take advantage of adaptive modulation and coding, meaning that inside one BS sector each CPE may use the most suitable modulation and coding type irrespective of the others (Smura, 2006).

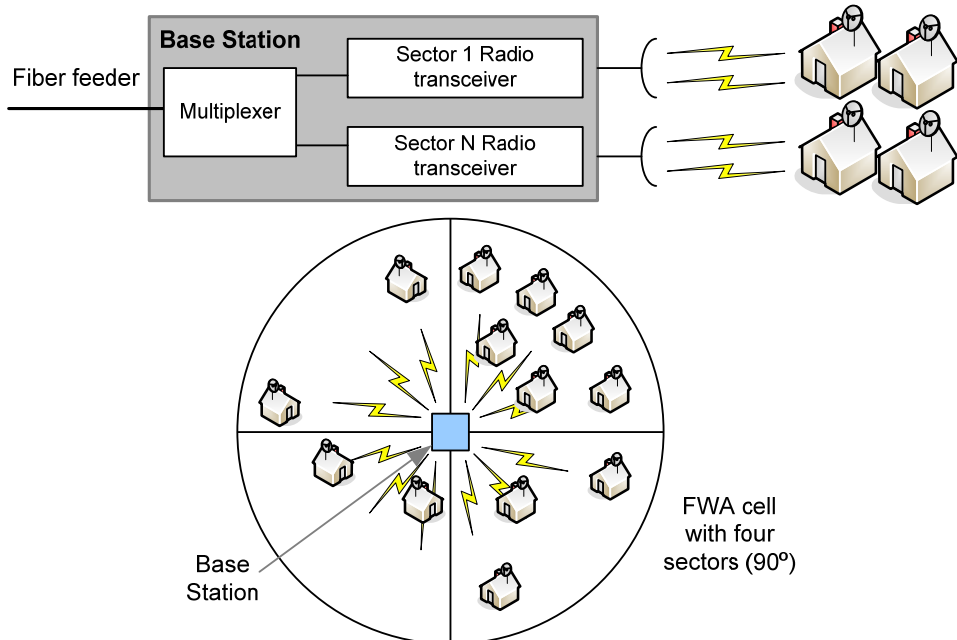


Fig. 6. Base Station components (Ufongene, 1999)

The base station equipment, like CPE, consists of two main building blocks: The antenna unit and the modulator/demodulator equipment (see Fig. 6 and Fig. 7). The antenna unit represents the outdoor part of the base station, and is composed of an antenna, a duplexer, a radio frequency (RF), a low noise amplifier and a down/up converter. The choice of antennas has a great impact on the capacity and coverage of fixed wireless systems.

The BS consists of one or more radio transceivers, each of which connects to several CPEs inside a sectorized area. In the BS one directional sector antenna is required for each sector.

Sector antennas are directional antennas and the beamwidth depends both on the service area and capacity requirements of the system. A BS with one sector using an omnidirectional antenna has a quarter of the capacity of a four-sector system (Anderson, 2003). The modem equipment modulates and mixes together each flow over the IF cable which is connected to the antenna unit.

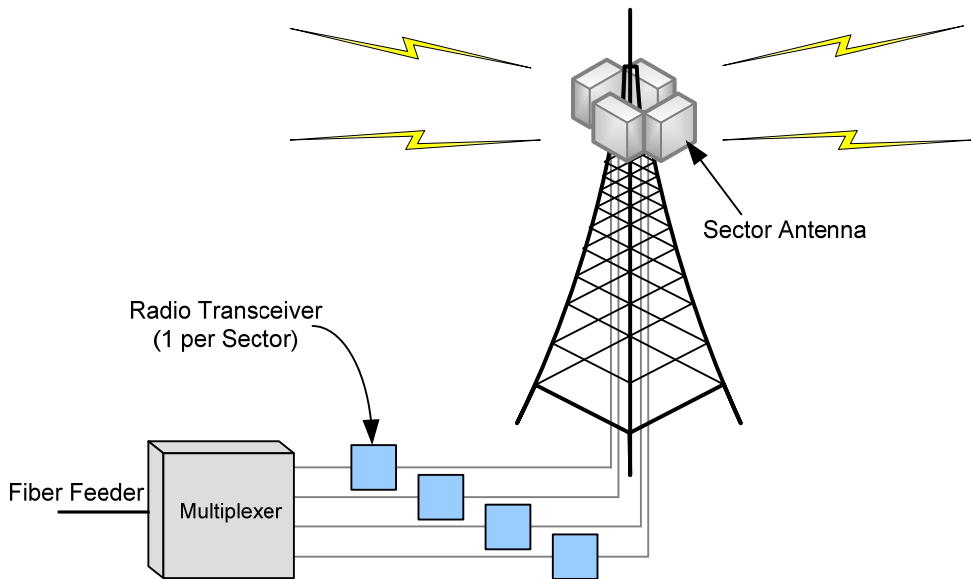


Fig. 7. Base Station components

As we can see in Fig. 7, each FWA base station consists of a number of sectors. The traffic capacities of these sectors depend most importantly on the modulation and coding methods, as well as on the bandwidth of the radio channel in use. The sector capacity is divided between all the subscribers in the sector's coverage area (Smura, 2004).

3. Techno-Economic Model

To support the new needs of the access networks (bandwidth and mobility), the proposed framework (Fig. 8) is divided into two perspectives (static and nomadic) and three layers. In the static perspective, users are stationary and normally require data, voice, and video quality services. These subscribers demand great bandwidth. In the nomadic/mobility perspective, the main preoccupation is mobility, and normally, the required bandwidth is smaller than the static layer (Pereira & Ferreira, 2009).

Focus of the wireless networks was to support mobility and flexibility while that of the wired access networks is bandwidth and high QoS. However, with the advancement of technology wireless networks such as WiMAX also geared to provide wideband and high QoS services competing with wired access networks recently (Fernando, 2008). The proposed model divides the area into several access networks (the figure is divided into 9

sub-areas, but the model can divide the main area between 1 and 36). The central office is located in the center of the area, and each sub-area will have one or more Aggregation Nodes (AGN) depending on the technology in use.

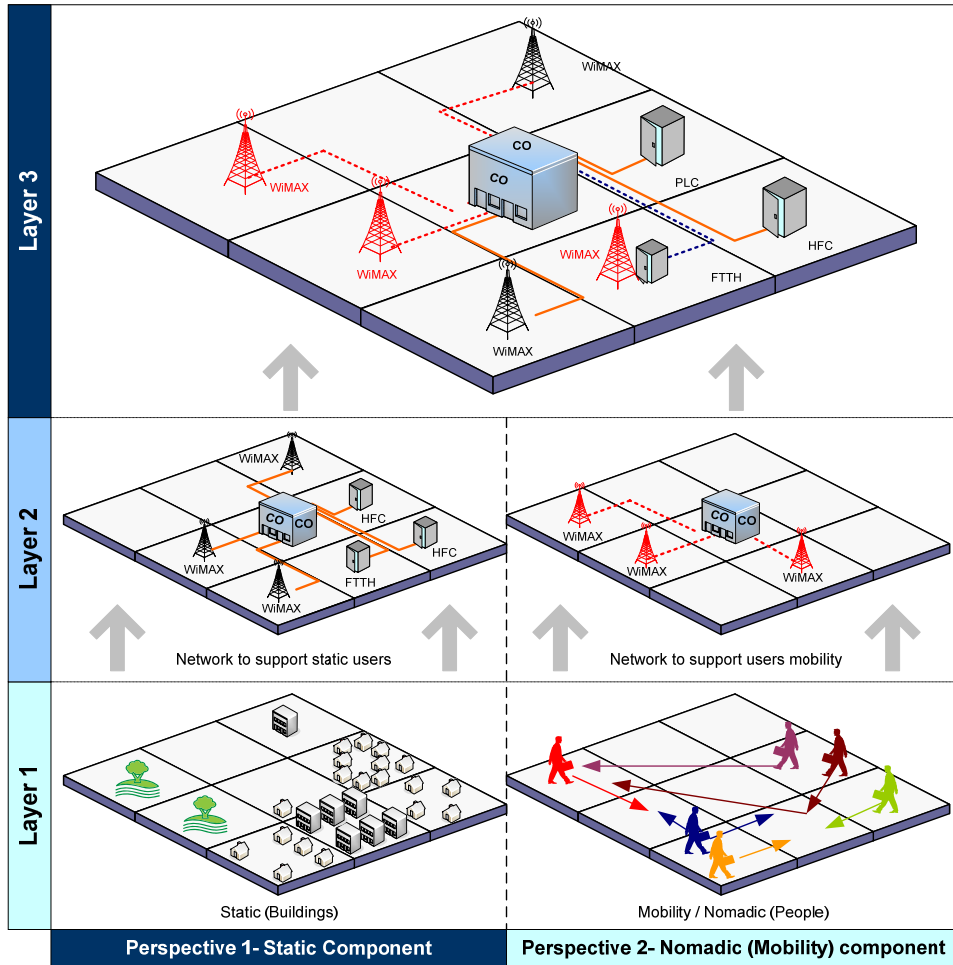


Fig. 8. Cost model framework architecture

As we can see in Fig. 8, the framework is separated into three main layers (Pereira, 2007a): (Layer A) Firstly, we identify the total households and SMEs (Static analysis) for each sub-area, as well as the total nomadic users (Mobility analysis). The proposed model initially separates these two components because they have different characteristics. In layer B, the best technology is analyzed for each Access Network, the static and nomadic components. For the static analysis we consider the following technologies: FTTH (PON), DSL, HFC, and WiMAX PLC. For the nomadic analysis we use the WiMAX technology. The final result of this layer is the best technological solution to support the different needs (Static and

nomadic). The selection of the best option is based on four output results: NPV, IRR, Cost per subscriber in year 1, and Cost per subscriber in year n. The next step (Layer C) is to create a single infrastructure that supports the two components. Bearing this in mind, the tool analyzes each Access Network which is the best solution (based on NPV, IRR, etc). Then, for each sub-area we verify if the best solution is: a) the use of wired technologies (FTTH, DSL, HFC, and PLC) to support the static component and the WiMAX technology for mobility; or b) the use of WiMAX technology to support the Fixed and Nomadic component.

3.1 Cost Model Structure

The structure of a network depends on the nature of the services offered and their requirements including bandwidth, symmetry of communication and expected levels of demand.

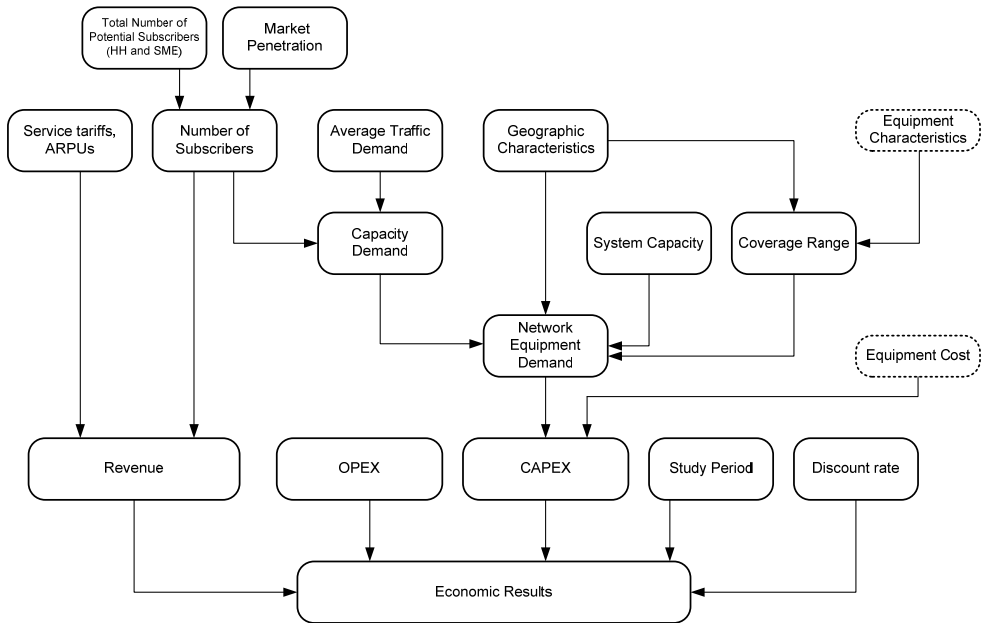


Fig. 9. Techno-economic parameters

As shown in Fig. 9, the techno-economic framework basically consists of the following building blocks (Montagne *et al.*, 2005): Area definition (geography and existing network infrastructure situation); Service definitions for each user segment with adoption rates and tariffs, such as network dimensioning rules and cost trends of relevant network equipment; cost models for investments (CAPEX) and operation costs (OPEX); Discounted cash flow model; Output metrics to be calculated.

The model analyzes several technical parameters (distances, bandwidth, equipment performance, etc.) as well as economic parameters (equipment costs, installation costs, service pricing, demographic distribution, etc.). The model simulates the evolution of the

business from 5 to 25 years. This means that each parameter can have a different value each year, which can be useful for reflecting factors that evolve over time.

3.1.1 General Model Assumptions

Our model framework defines the network starting from a single central office (or head-end) node and ending at a subscriber CPE. At the CO, we consider only the devices that support the connection to the access network (OLT).

Users are usually classified in four main categories: Home (residential customers), SOHO (Small Offices and Home Offices), SME (Small- to Medium-size Enterprises) and LE (Large Enterprises). The tool implements a methodology for the techno-economic analysis of access networks for residential customers and SME.

Network Component	Component Costs	Description
Physical Plant component costs	Housing	The housing cost is the cost of building any structures required (e.g., remote terminal huts and CO buildings), and includes the cost of permits, labor, and materials.
	Cabling	The cabling cost is the cost of the materials (i.e., the cost of the necessary fiber optic, twisted pair, or coax cables).
	Trenching	The trenching cost is the cost of the labor required to install the cabling either in underground ducts (buried trenching) or on overhead poles (aerial trenching).
Network Equipment	Equipment needed between CO and subscriber house	The electronic switches and/or optical devices (e.g., splitters) needed to carry the traffic over the physical plant.
	Subscriber Equipment	The price and other properties of the Access node, as well as the nature of the CPE unit, depend strongly on the access technology.

Table 1. General Model Assumptions

Access networks (for Wired technologies) have two separate but related components (Weldon & Zane, 2003): physical plant and network equipment (see Table 1). The physical plant includes the locations where equipment is placed and the connections between them. The physical plant costs depend primarily on the labor and real estate costs associated with the network service area, rather than on the specific technology to expand.

Access network costs can be grouped into two categories (Baker *et al.*, 2007): the costs of building the network before services can be offered (homes passed), and the costs of building connections to new subscribers (homes connected). More specifically, the homes passed portion of costs consists of exchange/CO fit out, feeder cables and civil works, cabinet and splitters, and distribution cables and civil works. The deployment cost calculations assumptions suppose that all construction work required to provide service to all homes passed takes place during the first year (deployment phase). However, only the necessary electronic equipments are deployed in the CO as well as the aggregation nodes to accommodate the initial assumption for the take rate.

3.1.2 Input Parameters

As mentioned beforehand, the definition of the input attributes is fundamental to obtain the right outputs. The model divides the inputs into two main categories: general and specific input parameters. General parameters are those that describe the area and service characteristics and are common to all the technologies. The specific parameters are those that characterize each solution, in technological terms.

These parameters are divided into three main groups: Equipment Components; Cable Infrastructure and Housing. The housing cost is the price to build any structures required in the outside plant (Cabinets, closures, etc.) This plant corresponds to the part between CO and the subscriber house. With regard to the cable infrastructure, the percentage of new cable corresponds to the need of the new cable required, and the percentage of new conduit parameter takes into account both underground and aerial lines. The civil work cost is based on the above mentioned parameters (for example: % of new conduit (Underground/Aerial), etc.) and on the Database cost. The cost of the labor also takes into account the cabling either in underground ducts (buried trenching) or on overhead poles (aerial trenching).

To build a new network or upgrade an existing one, an operator has to choose from a set of technologies. The cost structure may vary significantly from one technology to the other in terms of up-front costs, variable cost and maintenance costs. Each technology type has elements which are dedicated, like modems and shared elements (shared by many users) such as cabinets, optical network units, base stations and cables.

While some costs like equipment pricing, are easy to compute given the data in the Cost Database, because they do not depend on network topography, the per subscriber cabling costs (i.e. trenching and fiber) and equipment housing costs (which depend on distance and density) do, so they require optimization (Weldon & Zane, 2003).

A number of choices, assumptions, and predictions have to be made before proceeding to the techno-economic analysis of a broadband access network. These include the selection of the geographical areas and customer segments to be served, the services to be provided, and the technology to be used to provide the services (Smura, 2006). As we have seen above, the definition of the input attributes is fundamental to obtain the right outputs. Then, we define three main activities: Area Definition (Area parameters), Requested Services (Service parameters), Commercial Parameters and Type of Access.

3.1.3 Output Results

The financial analysis requires several outputs from the tool. The financial analysis is basically focused on the following steps: to compute the amount of equipment that needs to be installed each year for providing the service; to compute the amount of money spent on operational costs (Operations and Maintenance, Customer Support, Service Provisioning, Marketing); to compute the yearly income, taking into account that existing customers pay for 12 months; to compute the net profit obtained each year; and the NPV (Net Present Value) of the yearly profits. The calculated outputs are presented in Table 2:

Output	Description
Cost per subscriber	Average cost divided by all subscribers reachable with the system.
Cost per home passed	Average cost divided by all homes reachable with the system. The cost per home passed will include both the up front costs of equipment and installation and the ongoing costs of maintaining and managing the network.
CAPEX	Investments costs
OPEX	Operation costs
Installation cost	Costs for equipment installation
Total expenses	CAPEX + OPEX
Total revenue	The total amount customers will pay for their telecommunications services.
Life Cycle Cost	Is defined as the sum of global discounted investments and global discounted running costs. This gives the total costs for constructing and running the network over the study period.
Profit per year (cash flow)	The Cash Balance (accumulated discounted Cash Flow) curve generally goes deeply negative because of high initial investments (Monath <i>et al.</i> , 2003). Once revenues are generated, the cash flow turns positive and the Cash Balance curve starts to rise.
Ending Cash Balance (or Cumulated Cash Flow)	The balance in the Cash Account at the end of the reporting period and, therefore, on the ending balance sheet.
Payback Period (Months)	First year with positive
Net Present Value (NPV profit)	The NPV is today's value of the sum of resultant discounted cash flows (annual investments and running costs), or the volume of money which can be expected over a given period of time.
Internal Rate of Return (IRR)	IRR is the discount rate at which the NPV is zero. If the IRR is higher than the opportunity cost of money (that is, interest of an average long term investment), the project is viable.

Table 2. Output Results

3.2 Access Network Architecture

Our model studies the access part of the network, starting at the central office and ending at the subscriber's CPE (see Fig. 10). The cost model is based on a single central office, connecting the subscribers through several aggregation nodes.

The goal is to optimize the network in order to minimize the cost for a given performance criterion. The network is sized for the total number of Homes Passed. Consequently, all infrastructure costs (trenches, housing, electronics and fiber deployment) are incurred for all Homes Passed. Despite the costs of the CPE's, ports in the fiber node are only incurred when a home subscribes.

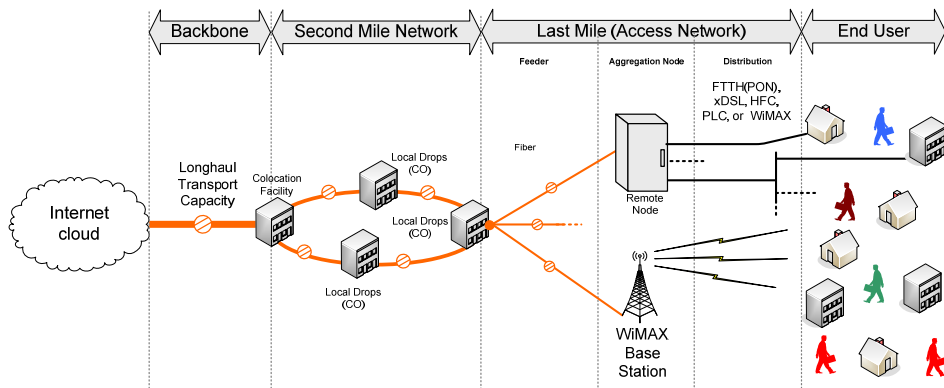


Fig. 10. Network architecture (Pereira, 2007a)

The access network architecture used in our model is divided into three main segments (Fig. 11): Inside, Outside, and End User. In the CO the different traffic flows are multiplexed/demultiplexed for further uplink connection to metropolitan and transport networks or, when it concerns local traffic, switched or routed back to the access network. For the CO we consider the following components: OLT ports, OLT chassis and passive splitters.

The outside segment is divided into three main parts: the feeder, aggregation Nodes and distribution (for HFC technology the distribution segment is divided into distribution and drop). Feeder segment comprise the network between the CO and the aggregation nodes. The model includes not only the cost of equipment (Fiber repeaters), but also the optical fiber cables, installation, trenches, and housing (street cabinets) costs. The ducts can be shared by several optical fiber cables. The aggregation nodes are located in access areas street cabinets. The components of these nodes depend on the technology. In the next section we will present the elements for the five technologies in study. The distribution network links the aggregation nodes with CPE. Like feeder networks, in distribution, the model includes not only the cost of equipment (copper, coax, and LV grid repeaters), but also the cables, installation, and trenches costs.

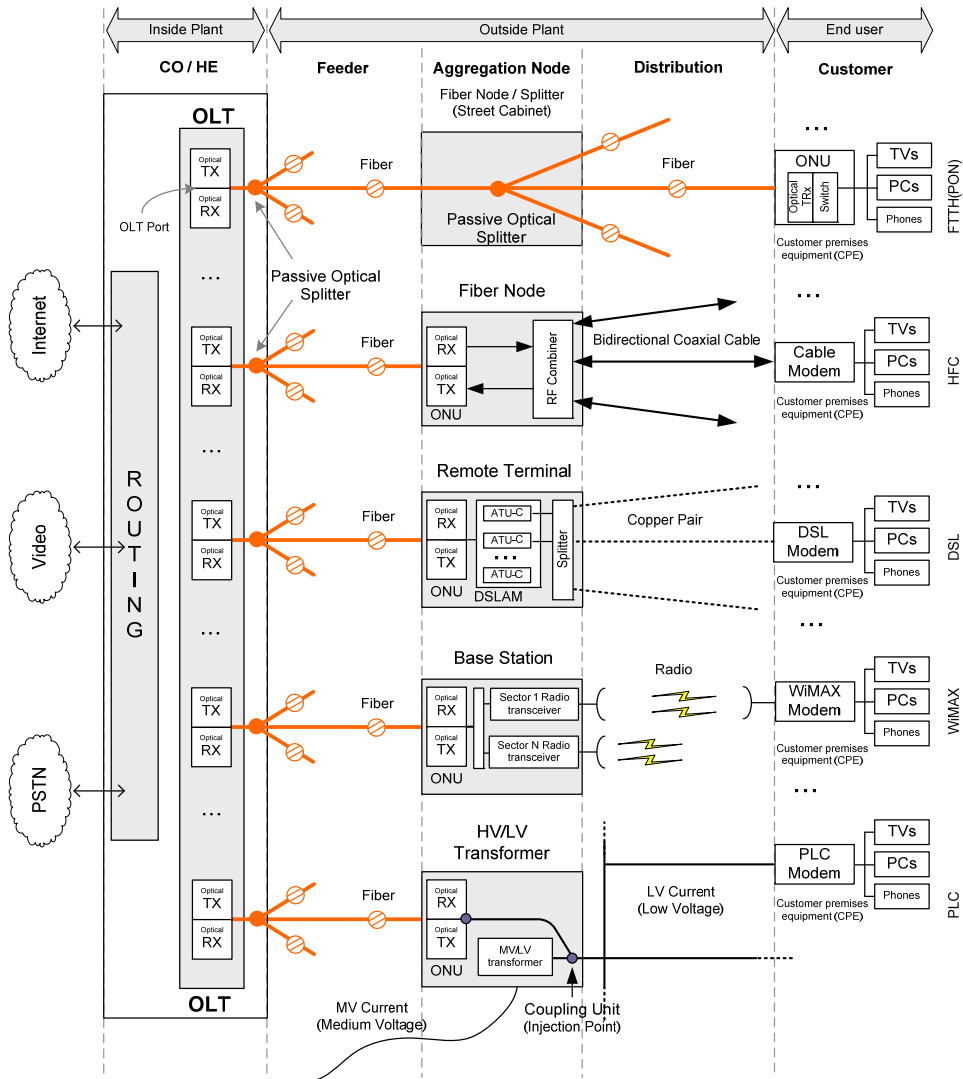


Fig. 11. Block diagram for Access Technologies (Pereira & Ferreira, 2009)

3.2.1 Access Network Components

Table 3 show the components used in our analysis. The components are divided into five segments (see Fig. 11). The inside plant and feeder segment components are common to all solutions. Optimally, there would eventually be 32 fibers reaching the ONTs of 32 homes (Pereira, 2007b). For example if the primary split is 1x4 and the secondary split is 1x8, then the network splitting ratio (or split scenario) will be 32. This means that a single feeder network supports 32 subscribers.

Inside Plant	Outside Plant			End User	
	Feeder	Aggregation Node	Distribution		
1) OLT ports 2) Chassis 3) Splitter (Primary Split) 4) Installation: Ports, chassis, and split.	1) Optical repeater 2) Repeater installation 3) Aerial/Buried trenches/ducts (Trenching costs) 4) Fiber Cable (cable cost) 5) Cable Installation	1) Splitter (Secondary Split) 2) Splitter Installation 3) Housing: Street Cabinet	1) Optical repeater 2) Repeater installation 3) Aerial/Buried trenches/ducts (Trenching costs) 4) Fiber Cable (cable cost) 5) Cable Installation	1) ONU 2) Fiber Modem 2) Installation	FTTH(PON)
		1) Node Cabinet equipment: ONU; DSLAM; Splitter; Line-cards; Chassis; Racks 2) equipment Installation 3) Housing: Street Cabinet	1) Copper regenerator / repeater 2) Repeater installation 3) Aerial/Buried trenches (Trenching costs) 4) Copper Cable (cable cost) 5) Cable Installation	1) xDSL Modem 2) Splitter 3) Installation	xDSL
		1) Fiber Node Cabinet equipment: O/E converter (ONU); RF combiner 2) equipment Installation 3) Housing: Street Cabinet	1) RF amplifier 2) Amplifier installation 3) Aerial/Buried trenches (Trenching costs) 4) Coaxial Cable (cable cost) 5) Cable Installation	1) Cable Modem 2) Splitter 2) Installation	HFC
		1) Local MV/LV Transformer Station equipment (TE equipment): O/E converter; Coupling unit (injection point) 4) Housing: Street Cabinet 2) Transformer Station equipment 3) equipment Installation	1) Repeater for LV network 2) Installation	1) PLC Modem 2) Installation	PLC

Table 3. Components used for wired technologies

The aggregation node, distribution and end user segments have different components, depending on each technology. In this table the components for the four wired technologies used in the model are presented.

The components for WiMAX technology are presented in the next section (see Table 4). However, the inside plant and feeder components are the same as the wired technologies.

3.2.2 Access Network Architecture for WiMAX

a) System Architecture

Fig. 12 shows the WiMAX system architecture used in our model. The “air” segments can replace the distribution and drop segment presented in Table 3.

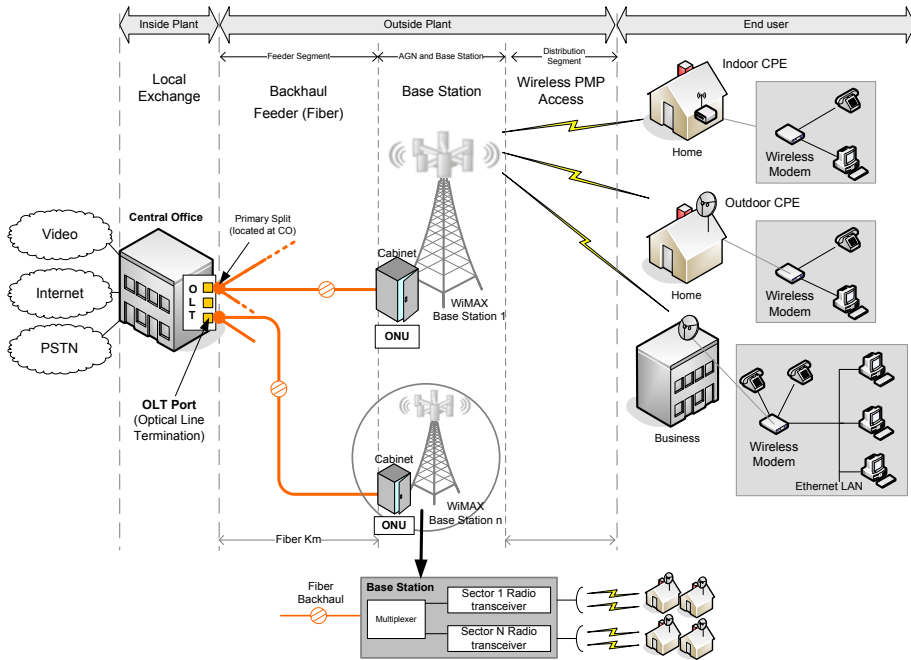


Fig. 12. Block Diagram of the baseline WiMAX system architecture

b) Components

According to the network architecture, the radio access network basically includes base stations, sites and “last mile” transmission (Wang, 2004). We therefore assume that the architecture is composed of a BS in the central end, a station in the subscriber side, and a PMP topology (between BS and CPE).

For capacity limited deployment scenarios it is necessary to position base stations with a BS to BS spacing sufficient to match the expected density of end customers. Data density is an excellent metric for matching capacity to market requirements. Demographic information including population, households and businesses per sq Km is readily available from a variety of sources for most metropolitan areas. With this information and the expected services to be offered along with an expected market penetration, data density requirements are easily calculated (WiMAX Forum, 2005b).

Base stations (towers) and base station equipment does not need to be installed in totality during the first year, but can be displayed over a period of time to address specific market segments or geographical areas of interest for the operator. However, in an area with a high number of potential subscribers, it is desirable to install a sufficient number of base stations to cover an addressable market large enough to quickly recover the fixed infrastructure cost (WiMAX Forum, 2004).

As presented in the previous figure, the common cost elements assumed in our model are in terms of Base Station the upfront costs; sector costs (including transducer and antenna); and Installation cost (co-siting, new site); Customer Premise Equipment (CPE): Indoor/Outdoor CPE; and Installation of the CPE, besides Operation, Administration and Maintenance (OAM).

Outside Plant		
Aggregation Node (Base Station)	Distribution (Wireless PMP Access)	End User
1) Site acquisition 2) Site lease 3) Civil works BS 4) Housing Cabinet / Closures for each BS 5) PMP equipment (multiplexer + cost sector X # sectors per BS) 6) BS installation Cost (including sectors) 7) ONU (BS) and Installation	air	1) WiMAX terminal (include: Antenna, Transceiver, Radio Modem) 2) Installation

Table 4. WiMAX architecture components

It is rather important to calculate the required number of FWA base stations and sectors to fulfill the traffic capacity demands of all the subscribers in a given service area (Smura, 2004). The first step is the prediction of aggregate subscriber traffic in the service area. The number of the required BS is calculated as a function of the demand specified by the service area to be covered; average capacity required per user during busy hour; and number of subscribers within the coverage area (Johansson *et al.*, 2004). When radius of service-area cell is small, there are many cells of total service area. When the radius of the service-area cell is large, the number of cells is smaller in a total service area. This is the reason why total construction relative cost is decreasing when radius of service area is increasing.

3.3 Geometric Model Assumptions

The definition of the geometric model is required to calculate the length of trenches, ducts and cables. Some of the construction techniques are aerial, using string along utility poles (mostly rural areas); trench, digging up earth and then lay a new conduit and fiber (used in urban areas); and pull-through, running through existing underground conduits. Since each technology has different characteristics, the model assumes different assumptions for the several access technologies, which are described in the previous sections.

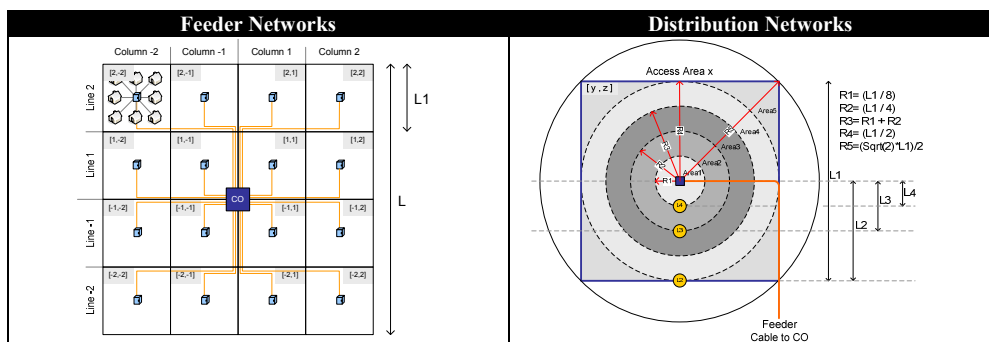


Table 5. Geometric model for Feeder and Distribution networks

In our work we consider that trench length represents the civil work required for digging and ducting – the model does not make distinction between aerial (overhead poles) and

buried (underground ducts). However, the costs are more significant where infrastructure must be buried than where it can be installed on existing poles (usually, aerial installation is almost twice as inexpensive as when the infrastructure is buried).

4. Results

4.1 Scenario description

		Value	Trend (% per year)
Years (Study Period)		15	
Geographical Area Description		Urban	
Total Access Networks (Sub-areas)		4	
Area Characteristics	Area Size (Km2)	47	0,00%
	Access Network area (Km2)	11,75	
	Residential		
	Total Households (potential subscribers)	11510	1,10%
	Households Density (Households / Km2)	245	
	Population Density (people/Km2)	250	3,80%
	Population	11.750	
	Inhabitants per household	1,02	
	Technology penetration rate (expected market penetration)	40,00%	8,00%
	Number of subscribers	4.604	
	Average Households per building	6	
	Number of buildings in serving area (homes/km2)	1918	
	SME (small-to-medium sized enterprises)		
	Total SME in Area	2502	1,50%
	Technology penetration rate (expected market penetration)	30,00%	5,00%
	Total SME (customers)	751	
	Nomadic Users		
	Total Nomadic Users	1950	15,00%
Service Characteristics	Residential		
	Required Downstream bandwidth (Mbps): Avg data rate	8	1,2%
	Required Upstream bandwidth (Mbps): Avg data rate	0,512	1,2%
	SME		
	Required Downstream bandwidth (Mbps): Avg data rate	12	1,2%
	Required Upstream bandwidth (Mbps): Avg data rate	0,512	1,2%
	Nomadic Users		
	Required Downstream bandwidth (Mbps): Avg data rate	2	2,0%
	Required Upstream bandwidth (Mbps): Avg data rate	0,512	2,0%

Pricing	Residential		
	One-time Activation/connection fee (€)	100	0,15%
	Subscription fee (€ / month)	50	0,15%
	SME		
	One-time Activation/connection fee (€)	150	0,15%
	Subscription fee (€ / month)	75	0,15%
	Nomadic Users		
	One-time Activation/connection fee (€)	75	0,15%
	Subscription fee (€ / month)	45	0,15%
Discount Rate (on cash flows)		0%	

Table 6. General Input Parameters for Access Network

The three main activities for the scenario description are: area definition, definition of the set of services to be offered, and the pricing. Table 6 shows the general input parameters used in our model and tool.

The trends for each parameter are presented in the last column. This scenario is defined for a study period of 15 years and for an urban area (City located in a remote area). The definition of the area type is essential because several costs are influenced by the fact that it is either an urban or a rural area.

Other important parameter is the definition of the number of access networks in which we want to divide the studied area (between 1 and 36). This scenario assumes the division of the area into 4 sub-areas (or access networks). Next, the definition of the number of households (HH), SMEs and nomadic users is also required for each access network (Table 7).

	Access Network 1	Access Network 2	Access Network 3	Access Network 4	Total Area (Year 1)
HH:	9000	2000	500	10	11510
SME:	1000	5000	1000	2	7002
Nomadic Users:	100	850	0	1000	1950

Table 7. Input Parameters: Total subscribers for each Access Network

As mentioned before (see Table 5), the access areas can be divided into five circular areas (between 1 and 5). This way, we can distribute the users in each access area, and calculate the trenches and required cable for the wired technologies (Table 8). When using wireless technologies, this structure is a good option to manage the required base stations for each access area more effectively.

	Access Network 1		Access Network 2		Access Network 3		Access Network 4	
	HHs	SMEs	HHs	SMEs	HHs	SMEs	HHs	SMEs
Area1	50%	10%	20%	20%	20%	20%	5%	20%
Area2	20%	20%	20%	20%	20%	20%	10%	20%
Area3	15%	40%	20%	20%	20%	20%	15%	20%
Area4	10%	20%	20%	20%	20%	20%	20%	20%
Area5	5%	10%	20%	20%	20%	20%	50%	20%

Table 8. Input Parameters: Subscribers localization for each Access Network

4.1.1 Feeder and Distribution Network Parameters

As described in Fig. 11, the feeder segment corresponds to the network part between CO and the aggregation node. In the CO, our model considers the OLT equipment, and we assume that the primary splits are at the CO. Table 9 shows the parameters used for the feeder and distribution segment of the network.

Feeder Network Parameters		Distribution Network Parameters	
Technology		Technology	
Primary Split (located at CO)	04	FTTH(PON)	
OLT Chassis		Secondary Split (Street Cabinet)	08
Number of OLT card slots per OLT Chassis	16	Split Ratio: Subscribers per OLT port	32
OLT Cards (only for Subs not for HP)		xDSL	
Number of OLT ports per Card	08	xDSL technology	ADSL
Max. ONU's per OLT Port	64	ONU	
Downstream Rate (Mbps) per OLT port	622	Maximum DS Capacity per ONU (Mbps)	2000
Upstream Rate (Mbps) per OLT port	155	Maximum US Capacity per ONU (Mbps)	1000
Optical repeater and Copper regenerator		Remote Terminal DSLAM	
Distance between Optical Repeater (km)	30	DSLAM Units (Chassis)	6 Line Cards
Trench Parameters		Number of Line Cards (ATU-Cs) per DSLAM unit: Slots	6
Total Trench Length (Km)	10,28	DSLAM Line Card (only for Subs not for homes passed)	Line_card_ports_48
% of new trenches	65%	Number of port per line card (Max. subs per line card)	48
Street Cabinet Parameters		Downstream Rate (Mbps) per DSLAM line card port	8,00
% of new Street Cabinets/Closures	60%	Upstream Rate (Mbps) per DSLAM line card port	2,00
Max. # of Users per Street Cabinet (AGN)	2048 user	DSLAM Line Card Splitter	
Cable Parameters for feeder network		DSLAM Splitter Card	48 ports
% of new cable	60%	Remote cabinet capacity	
Cable type	Optical Cable 48Fiber	Max. Number of DSLAMs per cabinet	5
Capacity per fiber (Gb/s)	1	Copper regenerator/repeater	
		Distance Between Copper Repeater (km)	5
		HFC	
		ONU	
		Maximum DS Capacity per ONU (Mbps)	2000
		Maximum US Capacity per ONU (Mbps)	1000
		Number of Ports per ONU (for RF modem)	8
		RF node modem	
		Maximum DS Capacity per RF Node Modem (Mbps)	100
		Maximum US Capacity per RF Node Modem (Mbps)	100
		RF amplifiers (2-way)	
		Distance Between RF Amplifiers (2-way): km	2
		TAP equipment	
		Number of Drops per TAP	2
		WiMAX	
		ONU	
		Maximum DS Capacity per ONU (Mbps)	2000
		Maximum US Capacity per ONU (Mbps)	1000
		Base Station	
		Downstream Sector capacity (Mbps)	36
		Upstream Sector capacity (Mbps)	10
		Maximum sector throughput (Mbps): Capacity per sector	46
		Maximum number of sectors per base station	4
		Max. Base Station range - radius (km)	3
		CPE (only for Subs not for homes passed)	
		% of Indoor CPE	60%
		% of Outdoor CPE	40%
		PLC	
		ONU	
		Maximum DS Capacity per ONU (Mbps)	2000
		Maximum US Capacity per ONU (Mbps)	1000

LV Transformer equipment	
Number of MV/LV transformers per Transformer Substation	1
AVG Number of feeders per MV/LV transformer	8
Downstream LV TE capacity (Mbps):link between TE-CPEs)	25
Upstream LV TE capacity (Mbps)	25
Max. # HH per MV/LV transformer: (# Subsc per LV network)	24
PLC Repeater for all LV networks (all homes passed)	
AVG Length of the LV lines (m)	0,3
Maximum repeater reach (m)	0,325
Average number of repeaters in Single house	0
Average # repeaters in building (repeater in the meter room)	1,27

Table 9. Feeder and Distribution Network Parameters

The distribution segment links the aggregation nodes to the customers. The technologies used in our work are: FTTH(PON), xDSL, HFC, PLC, and WiMAX. As each solution embraces different characteristics, the previous table shows the parameters used for each one of them.

4.2 Results

This section presents the final results to support the new requirements of broadband access (fixed and nomadic users). Table 10 shows the results for the use of the several technologies to support the static layer (HH and SMEs). Each column corresponds to an access network. The output variables are represented in the lines: Payback period, NPV, IRR, Cost per subscriber in year 1, and cost per subscriber in year n.

		Access Network 1	Access Network 2	Access Network 3	Access Network 4	Total Area	
	# Fixed Users	10000	2500	1500	12	14012	
	# Nomadic Users	100	850	0	1000	1950	
FTTH	Payback Period	14	21	22	63	33	(Average)
	NPV	11.965.382 €	- 2.957.765 €	- 2.390.925 €	- 165.567 €	3.136.297 €	(Average)
	IRR	3,06%	-2,42%	-3,43%	-13,19%	-4,52%	(Average)
	Cost Subc Y1	10.852 €	16.153 €	18.444 €	48.135 €	25.811 €	(Average)
	Cost Subc Y15	153 €	189 €	249 €	207 €	203 €	(Average)
	CAPEX	52.220.733 €	18.694.854 €	11.437.130 €	237.165 €	82.589.882 €	(Sum)
	OPEX	9.016.542 €	2.407.516 €	1.403.593 €	15.745 €	12.843.396 €	(Sum)
WIMAX	Payback Period	14	14	13	55	27	(Average)
	NPV	3.821.570 €	978.222 €	890.269 €	- 140.025 €	1.523.938 €	(Average)
	IRR	2,33%	2,33%	3,32%	-12,04%	-2,13%	(Average)
	Cost Subc Y1	4.964 €	5.245 €	6.414 €	42.018 €	17.799 €	(Average)
	Cost Subc Y15	453 €	458 €	484 €	287 €	408 €	(Average)
	CAPEX	53.374.912 €	13.198.012 €	7.290.309 €	195.945 €	74.059.178 €	(Sum)
	OPEX	16.006.174 €	3.968.371 €	2.269.220 €	31.423 €	22.275.190 €	(Sum)
DSL	Payback Period	20	34	38	61	40	(Average)
	NPV	- 11.094.161 €	- 11.716.167 €	- 7.892.363 €	- 131.557 €	- 6.372.694 €	(Average)
	IRR	-2,21%	-7,53%	-9,02%	-12,74%	-7,99%	(Average)
	Cost Subc Y1	15.968 €	23.909 €	27.281 €	38.812 €	27.354 €	(Average)
	Cost Subc Y15	173 €	230 €	321 €	260 €	252 €	(Average)
	CAPEX	74.679.305 €	27.215.883 €	16.787.143 €	204.107 €	118.886.438 €	(Sum)
	OPEX	9.617.513 €	2.644.889 €	1.555.018 €	14.794 €	13.832.213 €	(Sum)
HFC	Payback Period	15	23	26	69	37	(Average)
	NPV	4.715.962 €	- 5.051.179 €	- 3.789.621 €	- 180.505 €	248.612 €	(Average)
	IRR	1,09%	-3,82%	-5,04%	-13,89%	-5,95%	(Average)
	Cost Subc Y1	12.606 €	18.167 €	20.812 €	50.991 €	28.137 €	(Average)
	Cost Subc Y15	155 €	194 €	264 €	214 €	211 €	(Average)
	CAPEX	59.287.426 €	20.721.462 €	12.789.876 €	251.477 €	93.050.241 €	(Sum)
	OPEX	9.199.269 €	2.474.322 €	1.449.543 €	16.371 €	13.139.505 €	(Sum)

PLC	Payback Period	30	46	51	51	44	(Average)
	NPV	- 37.581.298 €	- 18.359.891 €	- 11.979.733 €	- 133.062 €	- 16.564.697 €	(Average)
	IRR	-6,36%	-10,39%	-11,81%	-12,93%	-10,37%	(Average)
	Cost Subc Y1	21.257 €	29.714 €	34.382 €	38.622 €	31.420 €	(Average)
	Cost Subc Y15	221 €	267 €	351 €	220 €	264 €	(Average)
	CAPEX	98.485.189 €	33.056.567 €	20.378.811 €	202.299 €	152.122.866 €	(Sum)
Best Solution	OPEX	12.298.765 €	3.447.930 €	2.050.719 €	18.107 €	17.815.521 €	(Sum)
	Payback Period	FTTH	WiMAX	WiMAX	PLC		
	NPV	FTTH	WiMAX	WiMAX	DSL		
	IRR	FTTH	WiMAX	WiMAX	WiMAX		
	CostSubsc Y1	WiMAX	WiMAX	WiMAX	PLC		
	CostSubsc Yn	FTTH	FTTH	FTTH	FTTH		

Table 10. Broadband Access General Results

With these results we can identify the best solution for each access network. In general, the WiMAX technology is the best option for areas with fewer subscribers (area 3 and 4).

4.3 Sensitivity analysis

A sensitivity analysis is a systematic study of how an output result changes as the assumptions are varied. For the sensitivity analysis we use the tornado diagrams (graphical sensitivity analysis technique). A tornado diagram provides a graphical display of the sensitivity of some system responses to uncertainties in the various inputs of that system. The diagrams show the effects of uncertainties in each input variables on the output of the analysis. The following table shows the effect of these input variables (first column: coverage area, potential HH, etc.) on the output variables (Cost per subscriber, payback period, NPV, IRR, CAPEX, and OPEX).

Parameters Names	Low Parameter Values	High Parameter Values	Cost Per Subscriber		PaybackPeriod		NPV	
			Variation (Low Value)	Variation (High Value)	Variation (Low Value)	Variation (High Value)	Variation (Low Value)	Variation (High Value)
Coverage Area	-50%	50%	-0,1%	0,1%	0,0%	0,0%	1,3%	-1,3%
Potential HH	-55%	55%	4,9%	-1,8%	0,0%	7,1%	-31,3%	31,0%
Potential SMEs	-65%	65%	-2,9%	2,5%	7,1%	0,0%	-30,2%	29,9%
TakeRate HH	-50%	50%	4,0%	-1,7%	0,0%	7,1%	-28,0%	27,9%
TakeRate SME	-55%	55%	-2,5%	2,1%	7,1%	0,0%	-25,6%	25,5%
Required DS Bandwidth HH	-60%	60%	-46,4%	46,2%	-57,1%	264,3%	1366,1%	-1366,1%
Required DS Bandwidth SME	-55%	55%	-7,8%	7,6%	-7,1%	28,6%	152,3%	-152,3%
Activation Fee HH	-50%	50%	-0,1%	0,1%	7,1%	0,0%	-23,8%	23,8%
Month Fee HH	-40%	40%	-0,4%	0,4%	264,3%	-35,7%	-951,4%	951,4%
Activation Fee SME	-40%	40%	0,0%	0,0%	0,0%	0,0%	-2,2%	2,2%
Month Fee SME	-50%	50%	-0,1%	0,1%	35,7%	-7,1%	-163,3%	163,3%
CAPEX: Equipment	-50%	50%	-21,3%	21,3%	-21,4%	64,3%	334,9%	-334,9%
CAPEX: Equip. Installation	-55%	55%	-4,0%	4,0%	-7,1%	28,6%	127,9%	-127,9%
CAPEX: Housing	-50%	50%	-20,6%	20,6%	-28,6%	257,1%	680,0%	-680,0%
CAPEX: Cable	-55%	55%	0,0%	0,0%	0,0%	0,0%	0,2%	-0,2%
CAPEX: Civil Works	-50%	50%	-0,5%	0,5%	0,0%	7,1%	14,5%	-14,5%
OPEX: Network Operations	-55%	55%	-0,8%	0,8%	-7,1%	35,7%	168,5%	-168,5%
OPEX: Equipment	-50%	50%	-1,5%	1,5%	0,0%	7,1%	22,9%	-22,9%
OPEX: Equip. Installation	-55%	55%	-0,2%	0,2%	0,0%	0,0%	7,7%	-7,7%
OPEX: Housing	-50%	50%	-1,0%	1,0%	0,0%	7,1%	34,0%	-34,0%
OPEX: Civil Works	-50%	50%	0,0%	0,0%	0,0%	0,0%	0,4%	-0,4%
OPEX: Lease	-55%	55%	-0,5%	0,5%	-7,1%	28,6%	130,8%	-130,8%

			IRR		CAPEX		OPEX	
Coverage Area	-50%	50%	1,4%	-1,4%	-0,2%	0,2%	-0,1%	0,1%
Potential HH	-55%	55%	28,3%	-10,5%	-46,5%	46,3%	-46,6%	46,4%
Potential SMEs	-65%	65%	-22,5%	18,2%	-9,7%	9,7%	-9,8%	9,8%
TakeRate HH	-50%	50%	24,6%	-10,0%	-42,4%	42,2%	-42,4%	42,3%
TakeRate SME	-55%	55%	-18,9%	15,8%	-8,3%	8,1%	-8,3%	8,2%
Required DS Bandwidth HH	-60%	60%	1687,2%	-100,0%	-47,0%	46,8%	-38,3%	38,2%
Required DS Bandwidth SME	-55%	55%	158,6%	-151,4%	-7,9%	7,7%	-6,4%	6,3%
Activation Fee HH	-50%	50%	-23,6%	23,5%	0,0%	0,0%	-1,1%	1,1%
Month Fee HH	-40%	40%	-100,0%	711,0%	0,0%	0,0%	-5,4%	5,4%
Activation Fee SME	-40%	40%	-2,2%	2,2%	0,0%	0,0%	-0,2%	0,2%
Month Fee SME	-50%	50%	-167,2%	150,5%	0,0%	0,0%	-1,2%	1,2%
CAPEX: Equipment	-50%	50%	401,7%	-314,5%	-23,1%	23,1%	0,0%	0,0%
CAPEX: Equip. Installation	-55%	55%	124,6%	-128,5%	-4,3%	4,3%	0,0%	0,0%
CAPEX: Housing	-50%	50%	657,9%	-854,0%	-22,4%	22,4%	0,0%	0,0%
CAPEX: Cable	-55%	55%	0,2%	-0,2%	0,0%	0,0%	0,0%	0,0%
CAPEX: Civil Works	-50%	50%	14,4%	-14,4%	-0,6%	0,6%	0,0%	0,0%
OPEX: Network Operations	-55%	55%	152,4%	-174,0%	0,0%	0,0%	-10,3%	10,3%
OPEX: Equipment	-50%	50%	23,9%	-23,5%	0,0%	0,0%	-18,7%	18,7%
OPEX: Equip. Installation	-55%	55%	7,6%	-7,6%	0,0%	0,0%	-3,0%	3,0%
OPEX: Housing	-50%	50%	33,3%	-33,6%	0,0%	0,0%	-13,1%	13,1%
OPEX: Civil Works	-50%	50%	0,4%	-0,4%	0,0%	0,0%	-0,2%	0,2%
OPEX: Lease	-55%	55%	118,9%	-132,8%	0,0%	0,0%	-6,4%	6,4%

Table 11. Sensitivity analysis for WiMAX technology

The tornado diagrams are a series of horizontal bars (one for each variable) around the base value result. The big bars mean high impact and are on the top of the diagram. The bars decline in size to the smallest at the bottom, representing the parameter that causes least change to the base value. The red bars represent the Output for Low Value (negative variation in parameter), and the blue bars represents the Output for High Value (positive variation in parameter).

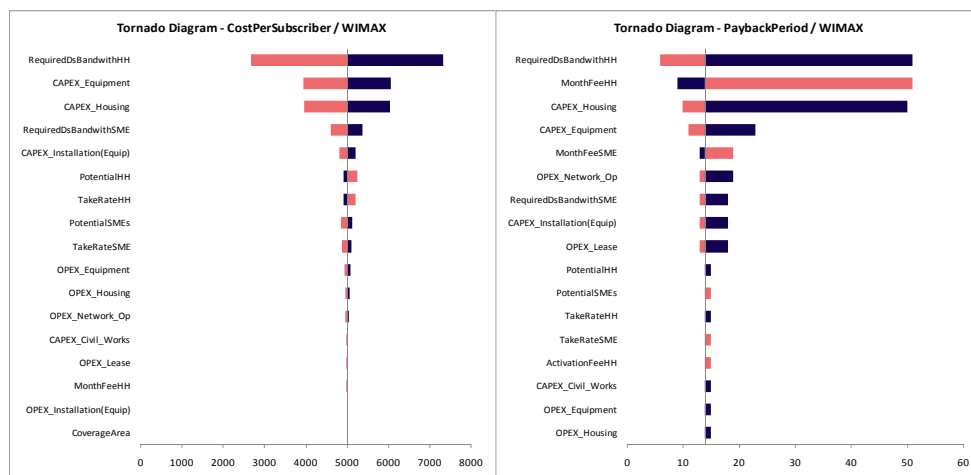


Fig. 13. Sensitivity analysis for WiMAX technology: Cost per subsc. And payback period

As we can see in graph 1 (Fig. 13), the three input variables which influence more the cost per subscriber are the required downstream bandwidth; equipment costs and housing costs. The three more critical variables that affect the payback period (graph 2) are bandwidth

(the increase of 60% in bandwidth implies an increase of 264% in payback period), households month fee (a decrease of 40% in this fee implies an increase of 264%), and housing costs (an increase of 50% of this feature leads to an increase of 257% in the payback period).

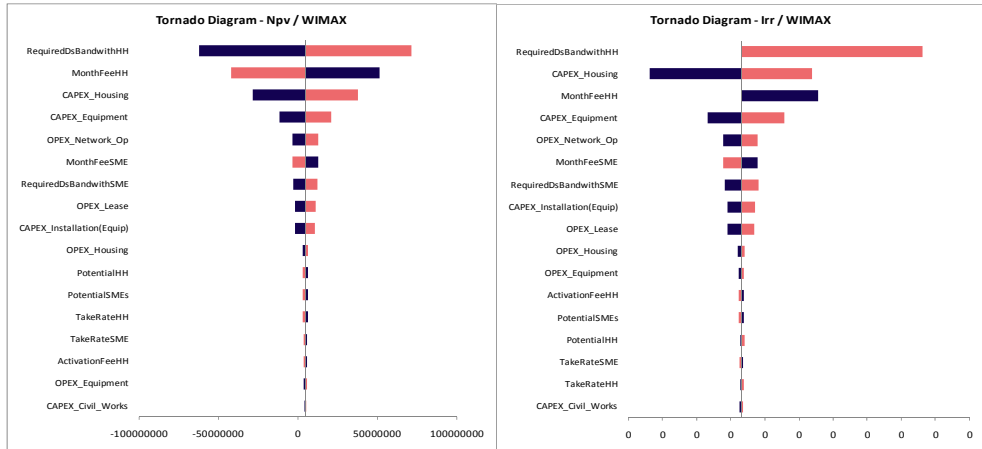


Fig. 14. Sensitivity analysis for WiMAX technology: NPV and IRR

For NPV and IRR (Fig. 14), the three most critical input variables remain the same as cost per subscriber and payback period (bandwidth, housing and equipment costs, and month fee).

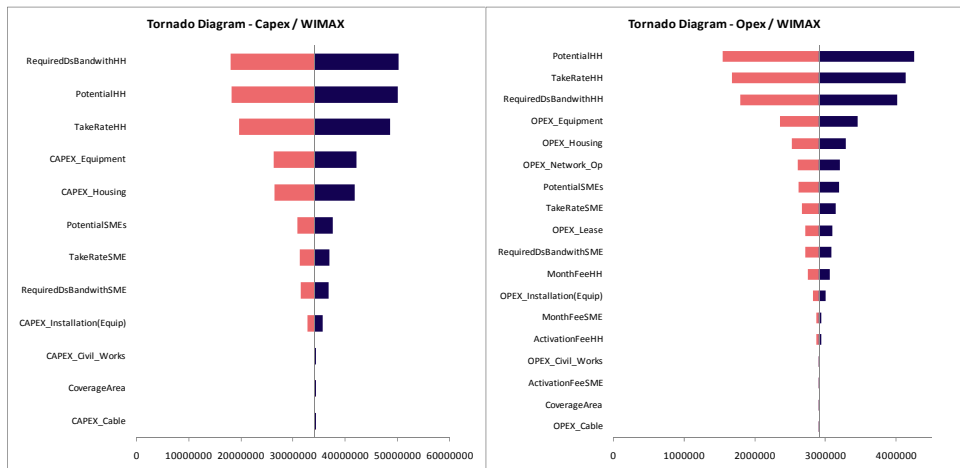


Fig. 15. Sensitivity analysis for WiMAX technology: CAPEX and OPEX

5. Conclusion

Nowadays access networks face two main challenges: the increasing bandwidth demand and mobility trends. All this will require fundamental changes to the operations of access networks, the functionality of network nodes and the architecture itself. The initial focus of wireless networks was to support mobility and flexibility, while for the wired access networks it was both bandwidth and high QoS. However, with the advances in technology, wireless solutions (such as WiMAX) have the capacity to provide both wideband and high QoS. WiMAX technology can also offer very high data rates, extended coverage and quickly deployable alternative to cabled access networks, such as fiber optic links, coaxial systems using cable modems, and Digital Subscriber Line (DSL) links. At present, WiMAX systems have the capability to address broad geographic areas without the costly infrastructure requirement of deploying cable links to individual sites. Besides, the technology may prove less expensive to disseminate and should lead to more ubiquitous broadband access.

In this context, we present a techno-economic model framework to support the bandwidth and mobility trends of access networks. The proposed tool performs a detailed comparison of WiMAX technology with different broadband access technologies (FTTH: PON, xDSL, HFC and PLC). For that, we identify the critical components of the WiMAX architecture. The produced results can analyze how the costs vary, calculating the cost per user, cost per homes passed, payback period, NPV, IRR, end cash balance, CAPEX, OPEX, and so on. For each sub-area, we describe the best solution, based on the output results.

Finally, we present the results of the sensitivity analysis. This analysis shows the effect of the input parameters (Coverage Area, Potential HH/SMEs, Take Rate, Required Downstream Bandwidth, Required Upstream Bandwidth, Activation Fee, Month Fee, etc.) on the output parameters (Cost per subscriber, Cost per Homes Passed, End cash balance, Payback period NPV, IRR, CAPEX, and OPEX.) and also identifies the critical parameters for several technologies. With this information it is possible to define better strategies for building broadband access networks.

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